Mirror Design Study for a Segmented HabEx System

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ABSTRACT

NASA is exploring telescope and mirror technology options to meet the demanding science goals of the proposed HabEx space telescope. A key priority for the HabEx mission concept would be to leverage affordable telescope solutions that can meet challenging telescope performance requirements with a demanding program timeline. The baseline approach for HabEx is to use an unobscured, monolithic primary mirror with a coronagraph to optimize system performance. NASA is performing an initial study to investigate the feasibility of a HabEx Lite concept which would not leverage a coronagraph and would therefore, have lower exoEarth yield as a consequence, but could provide system mass, cost, and schedule advantages. The HabEx Lite concept leverages replicated, ULE® mirror segments to provide an attractive, alternative telescope architecture to meet the HabEx threshold mission needs. We present the initial mirror design and performance assessment for the HabEx Lite concept.

Keywords: Replicated optics, segmented mirrors, large optics, HabEx

1. INTRODUCTION

Harris and JPL performed a high-level architecture trade for a 4-meter segmented primary mirror to explore affordable telescope options to meet the HabEx science goals. This concept is called the Low Cost 4 Meter (LC4M) telescope. The current baseline for the HabEx mission concept includes a monolithic, off-axis primary mirror that leverages a coronagraph for star light suppression[1]. The LC4M segmented HabEx system study assumes a star shade only approach for star light suppression causing a lower exoEarth yield, but could provide a more affordable option while still meeting HabEx mission science objectives[2]. This initial trade was performed to evaluate the feasibility of leveraging a segmented mirror telescope to provide an affordable solution to meet the mission requirements including meeting short and long-term system wavefront requirements. JPL's initial concept for the LC4M HabEx system is shown in Figure 1.

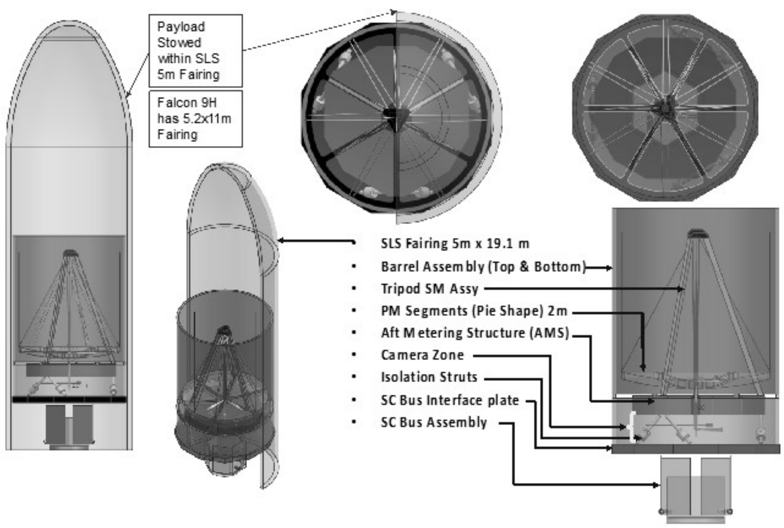


Figure 1. Low Cost 4-Meter Concept

JPL also established initial, high-level requirements for the LC4M segmented system. These requirements were used to perform the primary mirror assembly design and analysis. The requirements are shown in Figure 2.

	Parameter	Value	Note
Engineering Parameters	PM radius	8 m	Design parameter
	PM conic constant	1.0001	Design parameter
	PM segment size	TBD	Design parameter
	PM Surface Figure WFE	20 nm RMS	Following wavefront control
	PM surface microroughness	< 5 Å over 2-80 um	To limit scattered light
	PM segment stiffness	> 180 Hz free-free	For launch survivability and jitter avoidance
	Thermal control stability	± TBD K	Design parameter

Figure 2. Low Cost 4-Meter Concept Requirements

2. PRIMARY MIRROR ASSEMBLY BASELINE DESIGN

The initial primary mirror assembly design was performed with a goal of enhancing the mirror components including low mirror mass, high mirror rigidity, low percentage of aperture obscuration, high stability, low system complexity and risk while also optimizing affordability and rapid production. It was assumed that the mirror segments would have both rigid body and segment level figure actuation to meet the system level requirements. This assumption was re-visited as a potential activity for a future study to enable a passive, segmented system and is described in Section 4 of the paper. The resulting mirror segment properties for the segments are shown in Figure 3.

Characteristic	LC4M Value
Mass (kg) (Glass Only)	**31**
Physical Aperture (m^2)	**1.88**
Areal Density (kg/m^2) (Glass Only)	**16.46**
Major Dimension (mm)	**~1700**
Depth (mm)	**100.5**
1st Free-Free Mode (Hz)	**282**

Figure 3. Mirror segment design

This design leverages the maximum planned ULE boule size and depth available from Corning. This design is a relatively low mass mirror segment at 31 Kg with a relatively high first free-free mode of 282 Hz. In addition to the component level design, we also captured the primary mirror assembly total mass including all six segments and associated hardware. This is shown in Figure 4.

Sub-Assembly	Mass (kg)
Glass	186
Mount Pads	43.2
Reaction Structure (Backplane)	49.2
Rigid Body Actuators (6 per mirror)	37.6
Force Actuators (24 per mirror)	25.2
Potting Cups	2.9
Beam Launchers	5.4
Flexures (6 per mirror)	0.7
Total PMA Mass (6 Petals)	**350.2**
Mounted Mirror Assembly Areal Density (kg/m^2) (No Mass Contingency)	**31.0**

Figure 4. Primary mirror assembly mass

The system performance is critical to meet the science goals of the HabEx mission concept. While the system requirements for the star shade only concept are not as stringent as the coronagraph concept, the requirements are still very challenging for large aperture space-based imaging systems. The total wavefront error (WFE) budget for the telescope is shown in Figure 5. The allocation for the primary mirror assembly is 18 nm rms and a stability or drift allocation of 7 nm rms.

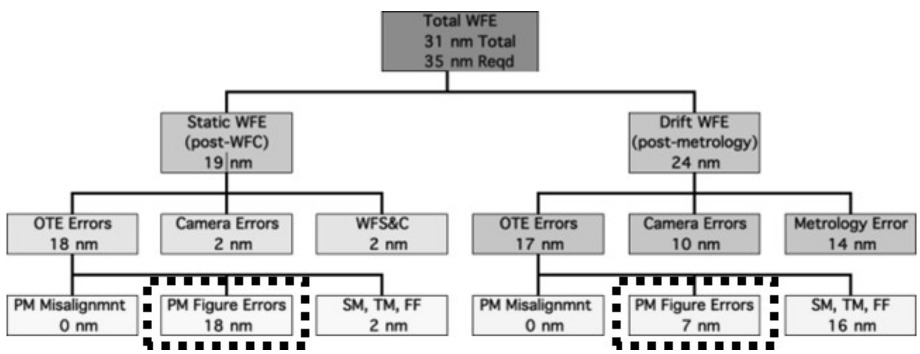


Figure 5. LC4M WFE budget

In addition to the allocations captured in the WFE budget, this study also investigated the short-term stability of the PMA with a very challenging requirement of 10 pm rms WFE over 10 minutes. The results of the initial PMA design against the allocated WFE budgets are shown in Figure 6.

Budget	Required (WFE RMS)	Predicted (WFE RMS)
PM Figure Errors (Static)	18 nm	**18.0 nm**
PM Figure Errors (Long Term Drift)	7 nm	**6.6 nm**
10 Minute Stability	10 pm	**9.8 pm**

Figure 6. LC4M WFE requirements

Many factors were included in the segment level WFE budget including segment-to-segment radius of curvature matching, polishing residual error, CTE and CTE uncertainty of the mirror material, measurement uncertainty, mount induced strain, 1-G release uncertainty, coating strain, thermal offset (built vs in-use), and many other smaller terms. In this analysis, it was assumed that the mirror segments all have 6 degrees of freedom for rigid body actuation and 24 figure control actuators per segment. The number and placement of actuators could be optimized in subsequent designs, creating additional margin against the required PMA WFE. The error budget for this design shows that it can meet the initial WFE allocation for the LC4M concept.

In addition to the component level design performed here, there are other design trades that are needed including technologies and strategies for mirror segment rigid body measurement and control, system wavefront measurement (ground and in-use) and control, and thermal control.

3. MIRROR MANUFACTURABILITY

The primary goal of the LC4M concept is to meet HabEx mission science requirements while optimizing affordability and minimizing production time of the telescope. Therefore, manufacturability was a key aspect of the primary mirror assembly baseline design. The design included considerations for the current state of the art in available mirror material and manufacturing processes. The size and depth of a primary mirror segment is such that is can be manufactured from a single boule of Corning's ULE material. This avoids the high cost and schedule of joining or flowing materials to create mirrors that are larger than a boule[3]. The design is also based on a ULE mirror that is constructed with low temperature fusion (LTF) bonds. This allows the design to leverage recent advances in mirror manufacturing such as Harris' Capture Range Replication (CRR™)[4]. CRR is the concept of starting with simple, flat components: a front and back facesheet and a lightweighted core. The plates and core are fused togther with LTF. The assembled mirror is then replicated to a surface figure that is within capture range of deterministic final finishing processes such as ion figuring[5], small tool polishing[6], or QED Technologies' magnetorheological finishing (MRF™)[7]. The CRR concept is captured in Figure 7.

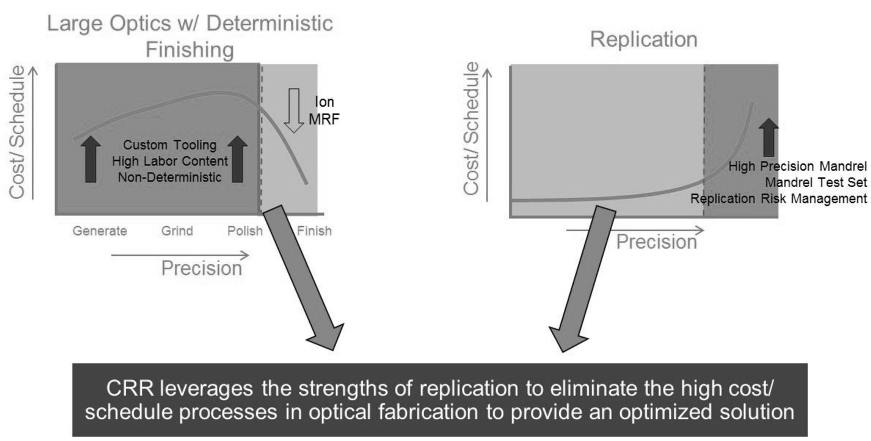


Figure 7. CRR description

The goal of CRR is to eliminate the high cost and long schedule steps of traditional optical fabrication processes such as shaping, grinding, and polishing. These steps are eliminated by replicating to a surface error that is within range of final finishing. In the past, others have developed processes to attempt to replicate directly to optical tolerances. The challenge with this approach is that the replication surface or mandrel needs to be even better that the final mirror surface figure tolerance and will also require a custom test set just for the mandrel, again with tighter tolerances than the final mirror test set. These requirements drive up the cost and schedule of replication which negate the original intended benefit, while still carrying significant risk in the ability to replicate to optical tolerances. CRR leverages existing deterministic finishing capabilities and facilities, significantly reduces the replication risks, and realizes the intended goal of replication- cost and schedule reduction.

Harris has been developing the CRR technology as part of a larger initiative called Advanced Mirror Construction (AMC). The AMC strategy is targeting several key areas to provide rapid, affordable large aperture mirrors for near and long-term space-based missions. The key initiatives of the AMC strategy are:

- Capture Range Replication (CRR™)
- Mirror structure and materials optimization
- Advanced component joining

The process flow for CRR on a ULE LTF mirror is shown in Figure 8.

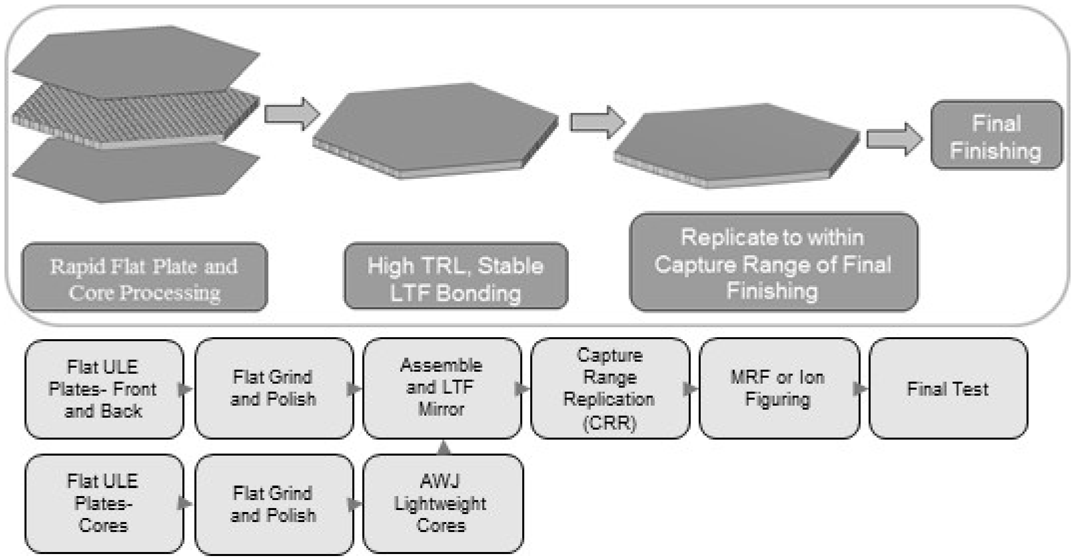
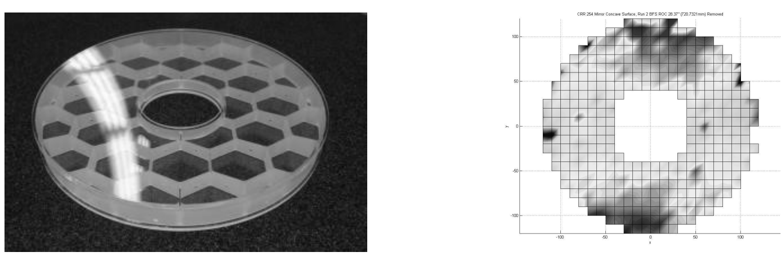


Figure 8. Process flow for ULE LTF CRR mirror

The CRR process was first demonstrated on small mirrors. Early tests were performed to slump thin, 200 mm diameter, ULE plates onto a spherical mandrel. The initial CRR process on a ULE plate achieved a ~3 µm P-V surface figure, as measured with a coordinate measuring machine (CMM). The part deviated from the mandrel by only ~1 µm P-V. A ULE faceplate with a center hole was replicated and was then bonded to a light weighted ULE core with a ULE backplate using LTF. The fully assembled ULE CRR mirror along with the resulting surface figure is shown in Figure 9.



(a) (b)

Figure 9: a) CRR ULE mirror and b) surface figure of a CRR ULE mirror as measured with a CMM

The fully assembled ULE CRR mirror was measured to be ~6.5 µm P-V surface figure with ~3 µm deviation from the mandrel used for CRR. This result is within final finishing capture range.

The process was then scaled to a 500 mm class, lightweight mirror. The results from these tests are shown in Figure 10.

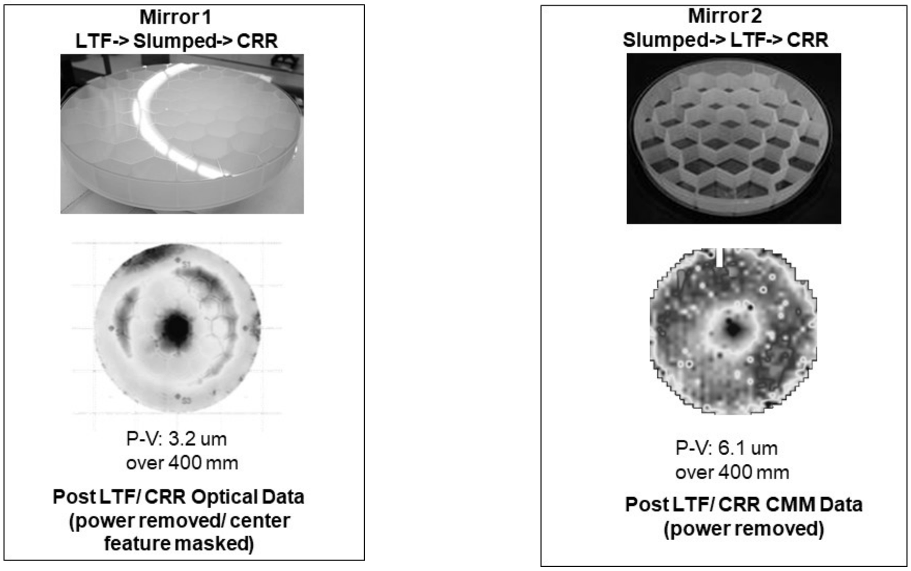


Figure 10: Results of ULE CRR mirror demonstrations

Again, the resulting mirror figure from these tests show that the mirror shape was within capture range of final deterministic finishing to achieve optical specifications. The CRR process is now being inserted into production at Harris for >1 meter sized optics. This process can be leveraged to optimize the production of primary mirror segments, including the segment designs for the LC4M concept, for affordability and rapid production.

4. CONCLUSION

Harris and JPL have performed an initial primary mirror assembly design study to support the LC4M design option for the HabEx mission concept. The results show that the segment mirror approach could meet the system requirements including mass and WFE budgets. Also, the design can leverage standard material boule size and advanced processes such as CRR to optimize the production of mirror segments for affordability and rapid production.

In addition, we performed an initial assessment of the advancements that would be needed to enable a passive mirror segment design that only had rigid body actuation. Some of the key advancements would be:

- Better mirror material CTE distribution and CTE distribution knowledge
- Multi-segment field-of-view phased metrology to enable better segment-to-segment radius matching
- Lower uncertainties in component and system level metrology
- Lower uncertainties in mirror models to reduce 1-G and mount induced errors

These key advancements combined with design considerations for mirror stiffness could enable a potential passive mirror segment solution for the LC4M concept.

The information presented about the HabEx concept is pre-decisional and is provided for planning and discussion purposes only. Portions of the research were carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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